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APPLICATION

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TITLE: **FUZZY LOGIC IMPEDANCE MISMATCH NETWORK FOR DSL QUALIFICATION**

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Cross-Reference to Related Applications

[001] This application relates to the following commonly assigned co-pending applications entitled:
"Estimation Of DSL Telephone Loop Capability Using CAZAC Sequence," Ser. No. ___________, filed June 30, 2003, "Time Domain Reflected Signal Measurement Using Statistical Signal Processing," Ser. No. ___________, filed June 30, 2003, all of which are incorporated by reference herein.

Background

[002] This disclosure relates generally to Digital Subscriber Line (DSL) telephone loop qualification, and more particularly to use of fuzzy logic for determining if the telephone loop is qualified to carry a DSL signal.

[003] Deployment of broadband services on a telephone loop is severely limited by the inherent properties of the copper cable and, in part, because initial deployment of the copper cable was aimed primarily at providing voice services to subscribers. Until the telephone loop electronics and plant are upgraded or replaced, as by installation of optical fiber loops, advanced digital signal processing holds great promise today for subscribers who desire broadband services such as high speed internet access, remote Local Area Network (LAN) access and switched digital video today. Technological advances have brought about Digital Subscriber Line (DSL) technology at high data rates, e.g., High-rate DSL (HDSL) and Asymmetric DSL (ADSL). For example, using ADSL technology, broadband signals are modulated by ADSL modems onto copper telephone loops at passband frequencies so that Plain Old Telephone Service (POTS) or another baseband service may be carried on the same pair of copper wires. Using the existing copper telephone loop is extremely cost effective as the installation of new cable and structure along with their associated labor and material costs are avoided.

[004] Deployment of technologies such as DSL, however may be limited by the transmission characteristics of the telephone loop. As such, before a particular subscriber

may utilize DSL technology for his or her broadband services, the broadband service provider has to determine or have determined the viability of deploying DSL to that subscriber. Thus, there is a need for a system and technique to determine whether the telephone loop is qualified to carry a DSL signal.

Brief Description of the Drawings

[005] Figure 1 is a block diagram of a DSL loop qualification system including a fuzzy impedance mismatch network in accordance with an embodiment of the invention;

[006] Figure 2 is a simplified schematic depiction of the DSL loop qualification system and fuzzy impedance mismatch network according to an embodiment of the invention;

[007] Figure 3 is a flow chart showing DSL loop qualification that determines the characteristics of the loop in accordance with an embodiment of the invention;

[008] Figure 4 shows the fuzzy inference system of Figure 1 with its inputs and outputs;

[009] Figure 5 shows the fuzzy membership function for change in capacitance C_1 (ΔC_1) and change in capacitance C_2 (ΔC_2) implemented in the fuzzy inference system in accordance with an embodiment of the invention;

[0010] Figure 6 shows the fuzzy membership function for change in inductance of L (ΔL) implemented in the fuzzy inference system in accordance with an embodiment of the invention; and

[0011] Figure 7 shows the fuzzy membership function for change in echo level divided by the echo level $\left(\Delta \varepsilon / \varepsilon\right)$ implemented in the fuzzy inference system in accordance with an embodiment of the invention.

Detailed Description

[0012] Deployment of DSL technology is limited by the transmission characteristics of the telephone loop. The transmission characteristics of the telephone loop depend on the length of the copper line, its gauge, the presence of bridged taps, the quality of splices, the integrity of the shielding, load coils, impedance mismatches and interference. Specifically, line loss increases with line length and attenuation increases with increasing frequency and decreases as wire diameter increases. There are particular points along the

telephone loop between the subscriber's termination and the originating central office (CO) where the loop is particularly susceptible to ingress noise. These points include, for example, the location of a bridged tap, the drop wire from the telephone pole to the home, and the wires within the home. At the aforementioned points ingress noise may be coupled into the loop. The presence of other telephone terminals connected to other pairs in the cable also leads to impulse noise. Furthermore, bridged taps create more loss, distortion, and echo. All these factors serve to limit the data transfer or information rate at which a subscriber may be connected to a broadband service provider over the telephone loop and are a major cause of connection problems subscribers currently face in making data connections via the public switched telephone network.

[0013] Service providers have several options to determine the environment the DSL signal operates in before they commit to service when a subscriber requests DSL service. The service provider may query the outside plant records to determine the loop configuration. Outside plant records more than likely would have been constructed from the original design records. In many cases, the records available are outdated and do not reflect changes that may have occurred in the outside plant as a result of maintenance and service orders. The end result is that the records are usually inaccurate and may not be relied upon to provide information required by the carrier to predict a telephone loop's ability to support DSL service. The approach described above does not provide the telephone loop characteristic information with a degree of accuracy required to confidently predict DSL performance over the loop.

[0014] One way to accurately calculate loop characteristic information to determine if the telephone loop is capable of carrying DSL service is to use a fuzzy impedance mismatch network 115 as shown in Figure 1. To determine the telephone loop length and other loop characteristics such as presence of bridge taps and insertion loss, a signal generator 105 generates impulse signals for transmission to the telephone loop 195 and CO 197. DSL qualification system 100 receives returned signals from telephone loop 195 and determines whether the telephone loop is capable of carrying DSL service. The returned signals received by DSL qualification system 100 include echoes of the impulse signals and noise and distortion generated from the various sources described above. In order to maximize the echoes to allow detection of the echo signal over noise and distortion, the

impedances Z_{out} 50 and Z_{loop} 75 should be mismatched as described in greater detail below.

[0015] The DSL loop qualification system 100 in Figure 1 includes the fuzzy impedance mismatch network 115 that receives output from signal generator 105. Fuzzy impedance mismatch network 115 may include impedance mismatch hardware 109 and a fuzzy inference system controller 113 in some embodiments. As shown in Figure 2, in one embodiment of the invention impedance mismatch hardware 109 includes two adjustable capacitors C_1 220 and C_2 230, one adjustable inductor L 240, one adjustable resistor R_m 210 and one series resistor R_s 205. Figure 2 is a simplified schematic depiction of the DSL loop qualification system and fuzzy impedance mismatch network of Figure 1. As shown in Figure 2, Z_{out} 50 is the output impedance of the fuzzy impedance mismatch network 115 coupled to signal generator 105. Z_{loop} 75 is the loop impedance of the telephone loop 195 that is shown in Figure 1 and Figure 2. Termination impedance Z_L 270 may be the impedance of the CO switching equipment or other termination hardware present in the CO. Termination impedance Z_L in Figure 1 may include the impedance of the ADSL splitter 156, Digital Subscriber Line Access Multiplexer (DSLAM) 150, Integrated Services Digital Network (ISDN) modem 170 and any other equipment coupled through connectors 180 present in CO 197.

[0016] In Figure 2, when the resistor R_m is bypassed (i.e. replaced with a close to zero resistance wire), the output impedance of the mismatch network 115 is $Z_{out} = R+jX$ where

$$R = \frac{R_s}{(1-\omega^2 LC_2)^2 + (\omega C_1 R_S + \omega C_2 R_s - \omega^3 LC_1 C_2 R_s)^2} \qquad \text{Equation 1}$$

and

$$X = \frac{\omega^3 LC_1^2 R_s^2 + 2\omega^3 LC_1 C_2 R_s^2 + \omega L - \omega C_1 R_s^2 - \omega C_2 R_s^2 - \omega^3 L^2 C_2 - \omega^5 L^2 C_1^2 C_2 R_s^2}{(1-\omega^2 LC_2)^2 + (\omega C_1 R_s + \omega C_2 R_s - \omega^3 LC_1 C_2 R_s)^2}$$

Equation 2

In Equation 1, the variable R corresponds to the real component of the output impedance Z_{out} and in Equation 2 the variable X corresponds to the imaginary component of the output impedance. Each of the components R_s, L, C_1 and C_2 in Equation 1 and Equation 2 is shown in Figure 2 and described above. The variable ω in Equation 1 may be defined as $\omega=2\pi f$ and corresponds to the radian frequency which is the frequency

generated by signal generator 105 that may be 50 Hertz or 60 Hertz. The telephone loop impedance Z_{loop} is $Z_{loop}=R(loop,Z_L)+jX(loop,Z_L)$ and includes a real component $R(loop, Z_L)$ and a reactive frequency dependent component $X(loop, Z_L)$. $R(loop, Z_L)$ and $X(loop, Z_L)$ are dependent on loop length, loop type and termination impedance Z_L. By mismatching Z_{loop} and Z_{out} (i.e. making ratio $Z_{loop}:Z_{out}$ as large as possible) using the fuzzy inference system controller 113, the echoes can be determined so that the time delay and other loop characteristics are accurately estimated.

[0017] Returning now to Figure 1, the DSL loop qualification system 100 may contain a measurement scope 120 to receive echo signals in the return path from telephone loop 195. The measurement scope 120 may be a microprocessor based instrument such as an oscilloscope including an analog-to-digital (A/D) converter and application software to detect, capture and process the received echo signal. The measurement scope outputs the echo value ε and change in echo value ε to fuzzy inference system 113. The echo value ε is the magnitude of the echo signal that may be calculated in volts or decibels by the measurement scope. The change in echo value ε is the difference between the echo value from a signal pulse with one set of values for C_1, C_2, and L and the echo value from the signal pulse transmit in the next iteration (described below) with another set of values for C_1, C_2, and L. DSL splitter 155 separates the data signals from the voice signals transmit over the copper lines of the telephone loop 195. In one embodiment of the invention shown in Figure 1, telephone loop 195 includes a wireline simulator 135 and loop plant 140. Wireline simulator 135 approximates the echo and noise signals of the loop plant 140 to allow the initial settings for the impedance mismatch hardware 109. Wireline simulator 135 may have access to loop plant records 140 that provide a good estimate of the expected echo signal for initializing the impedance mismatch hardware 109. Thus, wireline simulator 135 provides a reference model for the loop plant 140. The estimated echo signals from wireline simulator 135 travels through return path 198 to measurement scope 120. In some embodiments, telephone loop plant 140 is the path over which the DSL signal travels to the CO 197 and returns from the CO through return path 199 to measurement scope 120. The DSL signal is affected by various characteristics of the loop plant including copper cable length, gauge, presence of bridged taps, quality of splices, integrity of shielding, load coils, impedance mismatches and

interference. After traveling through loop plant 140, the DSL signal is transmitted to DSL splitter 156 in CO 197 that separates DSL data signals and voice signals that may have overlapped during transmission through loop plant 140. The DSL signal may then be transmitted to a DSLAM 150 or ISDN modem 170 for high-speed transmission to the internet service providers (ISP) network. If the DSL loop qualification system 100 has determined that the telephone loop is qualified to carry the DSL signal, DSL modem 160 and analog telephone modem 165, as shown in Figure 1, in one embodiment may verify the results of the DSL loop qualification system. Verification may occur by simultaneously sending and receiving an actual DSL signal as well as an analog modem signal over the telephone loop.

[0018] Referring to Figure 3, one embodiment of a technique for DSL loop qualification that determines the characteristics of the loop is shown. The technique shown in Figure 3 may be implemented in software executing on a processor. In one embodiment, the software may be executing on a processor located in measurement scope 120. In another embodiment, the software may be executing on a processor located in a separate central controller (not shown in Figure 1) in DSL qualification system 100. Wireline simulator 135, as described above, sets the initial values of impedance mismatch hardware 109 in oval 310. Next, in block 320, signal generator 105 transmits a signal pulse to the impedance mismatch hardware 109 and the loop plant 140 through DSL splitter 155. Measurement scope 120 receives an echo signal that may be noisy from loop plant 140 in block 330. The echo signal of maximum value is determined in diamond 340 by selecting a maximum from the previous and present values of echo signals. If the previous echo signal is the maximum (i.e. previous echo signal is greater than present echo signal) then the echo signal has reached its maximum. If the received echo signal is determined to be a maximum value in diamond 340, then the time delay between the echo signal and the transmit signal pulse is calculated in block 360. Other characteristics of the loop including the loop length, loop taps and insertion loss are also calculated based on the relative amplitude and time difference of the echo signal and the transmit signal pulse. Thus, the loop length may be determined by multiplying the time difference by the speed of signal propagation in the telephone loop (i.e. approximately the speed of light 299,792,458 meters/sec multiplied by a constant). Similarly, the loop taps and insertion

loss may be determined by examining the change in amplitude of the echo signal from the transmit signal pulse. If the received echo signal is not determined to be the maximum value in diamond 340, then the fuzzy inference system 113 adjusts the values of the impedance mismatch hardware 109 (described in greater detail below) in block 350. A signal pulse is again transmit in block 320 and the received echo signal 330 compared to the previous echo signal to determine a maximum value 340. This iterative process is continued until the maximum echo signal is determined and the loop characteristics are calculated.

[0019] Turning now to Figure 4, maximization of the received echo signal is performed by the fuzzy inference system 113. The fuzzy inference system 113 receives as inputs change in capacitance $C_1(\Delta C_1)$, change in capacitance $C_2(\Delta C_2)$, change in inductance $L(\Delta L)$, and the change in echo value versus the echo value $\left(\Delta \varepsilon / \varepsilon\right)$. The fuzzy inference system 113 outputs to the impedance mismatch hardware 109 a new change in capacitance $C'_1(\Delta C'_1)$, new change in capacitance $C'_2(\Delta C'_2)$, and new change in inductance $L'(\Delta L')$ using the fuzzy membership functions in Figure 5, Figure 6, and Figure 7. Fuzzy membership functions shown in Figures 5-7 are derived by incorporating all the known input-output behaviors, uncertainties and qualitative design objectives of the DSL qualification system. The output values $\Delta C'_1$, $\Delta C'_2$, and $\Delta L'$ become the input values ΔC_1, ΔC_2, and ΔL, respectively, for the fuzzy inference system 113 in the next iteration of maximization of the received echo signal shown in Figure 3. As shown in Figure 5, each fuzzy membership function is a triangle with corresponding labels NL, NM, NS, NSC, PS, PM, and PL. Fuzzy membership functions translate crisp input values into fuzzy output values. Thus, for example as shown in Figure 5, a crisp ΔC_1 input value of -15 μF would be translated into fuzzy output values of NL with degree of membership .25 (or 25%) and NM with degree of membership .73 (or 73%). The operation of the fuzzy inference system using the fuzzy membership functions and inputs to generate the outputs is described in more detail below.

[0020] The fuzzy inference system includes: (a) translation of a crisp input value into a fuzzy output value known as fuzzification , (b) rule evaluation, where the fuzzy output values are computed, and (c) translation of a fuzzy output to a crisp value known as

defuzzification. The fuzzy inference system 113 includes a range of values for the input and output variables as shown in Figures 5-7. Thus, for example as shown in Figure 5, ΔC_1 varies over the range -20 μF to 20 μF and as shown in Figure 6, ΔL varies over the range -10 μH to 10 μH. Labels for the triangular shaped membership functions for each of the input and output values of the fuzzy inference system are:

NL	negative large
NM	negative medium
NS	negative small
NSC	no significant change
PS	positive small
PM	positive medium
PL	positive large

Each of the input and output variables of the fuzzy inference system 113 uses a set of rules to maximize the echo value:

IF ΔC_1 is NL and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta C'_1$ is NM   Rule 1

IF ΔC_1 is NM and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta C'_1$ is NS   Rule 2

...

IF ΔC_1 is NL and $\Delta \varepsilon/\varepsilon$ is NM then $\Delta C'_1$ is NS   Rule A+1

IF ΔC_1 is NL and $\Delta \varepsilon/\varepsilon$ is NS then $\Delta C'_1$ is NSC   Rule A+2

...

IF ΔC_1 is NM and $\Delta \varepsilon/\varepsilon$ is NM then $\Delta C'_1$ is NS   Rule B+1

IF ΔC_1 is NM and $\Delta \varepsilon/\varepsilon$ is NS then $\Delta C'_1$ is NSC   Rule B+2

...

IF ΔC_2 is NL and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta C'_2$ is NM

IF ΔC_2 is NM and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta C'_2$ is NS

...

IF ΔC_2 is NL and $\Delta \varepsilon/\varepsilon$ is NM then $\Delta C'_2$ is NS

IF ΔC_2 is NL and $\Delta \varepsilon/\varepsilon$ is NS then $\Delta C'_2$ is NSC

...

IF ΔL is NL and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta L'$ is NM

IF ΔL is NM and $\Delta \varepsilon/\varepsilon$ is NL then $\Delta L'$ is NS

...

IF ΔL is NL and $\Delta \varepsilon/\varepsilon$ is NM then $\Delta L'$ is NS

IF ΔL is NL and $\Delta \varepsilon/\varepsilon$ is NS then $\Delta L'$ is NSC

...

The rules given above are derived by incorporating all the known input-output behaviors, uncertainties and qualitative design objectives of the DSL qualification system. Each label is given to each fuzzy input $\Delta C_1, \Delta C_2, \Delta L,$ and $(\Delta \varepsilon/\varepsilon)$ in a rule and the appropriate fuzzy output generated. The fuzzy inputs $\Delta C_1, \Delta C_2, \Delta L,$ and $(\Delta \varepsilon/\varepsilon)$ go through the fuzzy inference system to generate new crisp outputs $\Delta C'_1$, $\Delta C'_2$, and $\Delta L'$ to adjust the impedance of the mismatch network.

[0021] One example of the operation of the fuzzy inference system for selection of C_1 is described. During fuzzification, a crisp ΔC_1 input value of -15 μF is translated into fuzzy output values. Similarly, a crisp $(\Delta \varepsilon/\varepsilon)$ input value of -.9 is translated into fuzzy output values. Thus, as shown in Figure 5, -15 μF is fuzzified into NL with degree of membership .25 (or 25%) and NM with degree of membership .73 (or 73%). The fuzzy values for $(\Delta \varepsilon/\varepsilon)$ of -.9 are NM with degree of membership .33 (33%) and NL with degree of membership .67 (67%) as shown in Figure 7. Next, the entire set of rules in the fuzzy inference system is evaluated. Rules for which the IF-then rule conditions of ΔC_1 are satisfied are executed to generate the fuzzy output values of $\Delta C'_1$. For ΔC_1 with a value of -15 μF and $(\Delta \varepsilon/\varepsilon)$ with a value of -.9, Rule 1, Rule 2, Rule A+1 and Rule B+1 are executed to generate $\Delta C'_1$ values. Specifically, the $\Delta C'_1$ values are NM with degree of membership .25 (25%) for Rule 1, NS with degree of membership .67 (67%) for Rule

2, NS with degree of membership .25 (25%) for Rule A+1, NS with degree of membership .33 (33%) for Rule B+1. During defuzzification, the 25% NM, 67% NS, 25% NS, and 33% NS are combined using the center of gravity (COG) technique in order to produce a crisp output value. In the center of gravity technique, the membership functions of the variables such as ΔC_1 are truncated to their respective degrees of membership and combined. Next, the center of gravity (or balance point) of the combined membership functions that have been truncated is computed. The center of gravity may be computed as a weighted average of the truncated and combined fuzzy membership functions to produce the crisp output value. Using the COG technique produces the crisp output value of 8.76 μF for the value of $\Delta C'_1$. The value of C_1 is then decreased by 8.76 uF to adjust the overall impedance of the mismatch network. Selection of C_2 and L can be determined in a similar way as described above by the fuzzy inference system 113 to adjust the impedance of the mismatch network to generate a maximal echo signal. The time between transmission of the impulse signal and reception of its echo signal may be used to determine the length of the telephone loop and other loop characteristics. These loop characteristics may then be used to determine if the telephone line is capable of carrying DSL service.

[0022] While the present invention has been described with respect to a limited number of embodiments, those skilled in the art will appreciate numerous modifications and variations therefrom. It is intended that the appended claims cover all such modifications and variations as fall within the true spirit and scope of this present invention.

What is claimed is: